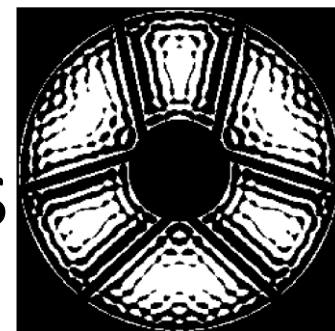


Jet Propulsion Laboratory
California Institute of Technology

Shaped Pupil Lyot Coronagraph and Apodized Pupil Lyot Coronagraph Design Studies for the WFIRST CGI



A J Eldorado Riggs (Jet Propulsion Laboratory)
California Institute of Technology

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Bijan Nemati (UAH)

John Krist (Jet Propulsion Laboratory)
California Institute of Technology

August 8, 2017

SPIE Optics + Photonics 2017

Paper # [10400-73](#)

1. Introduction on WFIRST CGI
2. CGI Spectroscopy Mode Improvements (SPLC)
3. CGI Disk Imaging Mode Improvements (SPLC)
4. APLC Investigations

CGI Coronagraph Design

- Goals:**
- Maximize science yield.
 - Minimize risk.

Design Parameters

Performance Metrics


- Contrast
- Throughput
- Spectral Bandwidth
- Field of View (IWA, OWA, angle)

Mask Properties

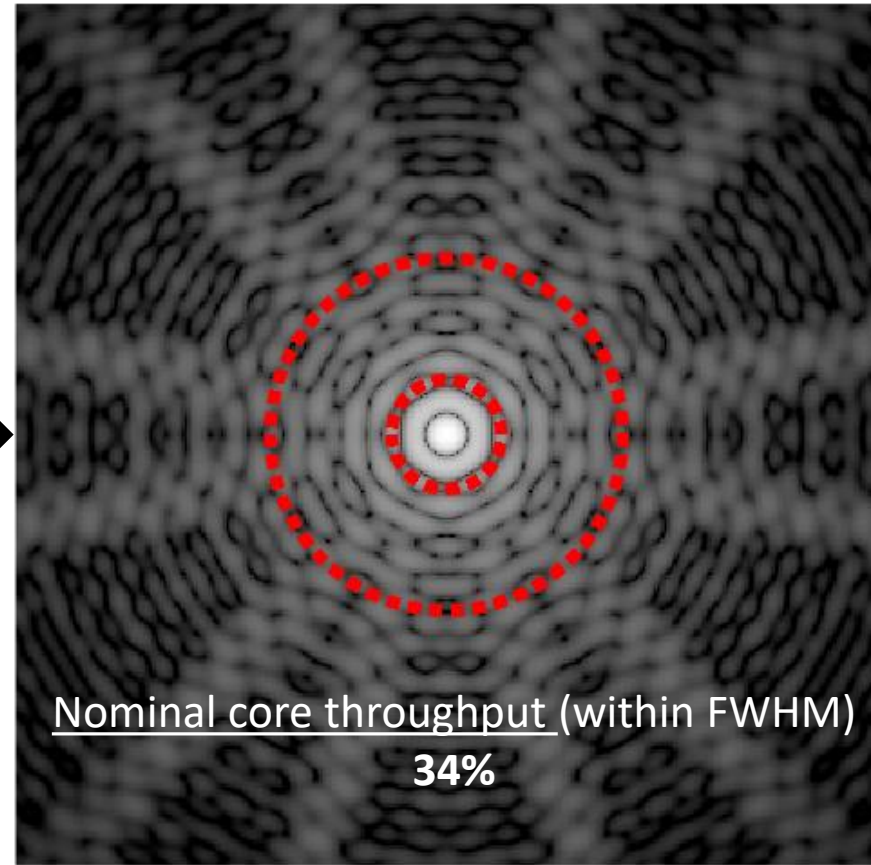
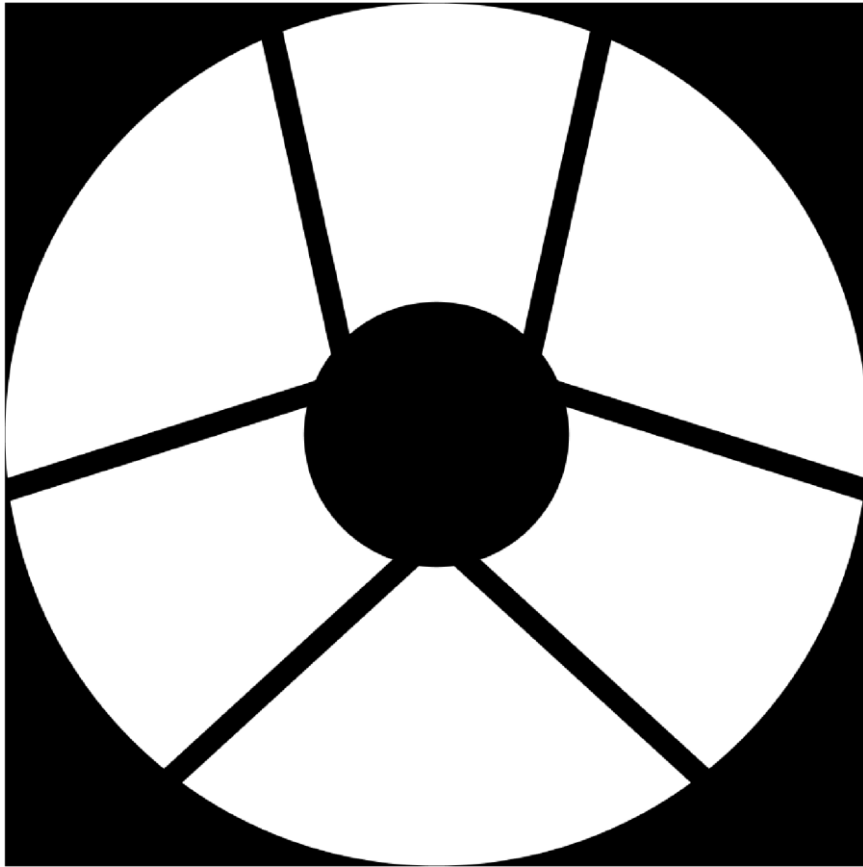
- Mask shapes
- Mask materials

Sensitivities to:

- Pointing jitter
- Wavefront jitter (coma, astig, focus)
- Primary mirror polarization aberrations
- Mask misalignment



*Most of the design work in
past year has been to
address sensitivities to
aberrations & misalignments.*

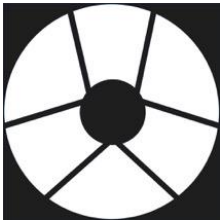


Coronagraphic core throughput:

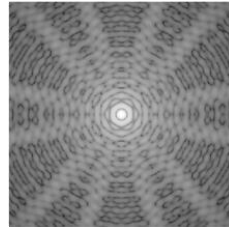
- *Open pupil:* ~18-24%
- *Annular pupil:* ~10-15%
- *WFIRST pupil:* ~4-6%

Types of WFIRST CGI Modes

WFIRST pupil

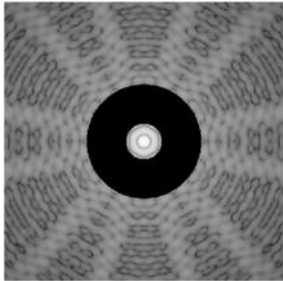


Nominal PSF



Three types of modes to achieve science goals:

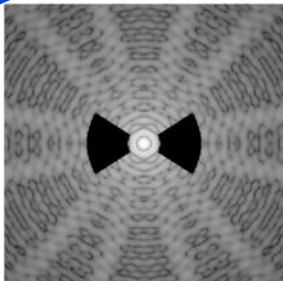
Notional dark hole regions:



1. **Hybrid Lyot Coronagraph (HLC):** *exoplanet & inner disk imaging*

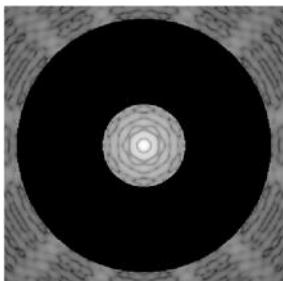
- 10% BW, 360° FOV, $\sim 3-9 \lambda_0/D$
- $\sim 4.5\%$ core throughput

• Trauger et al. JATIS 2016



2. **Shaped Pupil Coronagraph (SPC)** for IFS: *exoplanet spectroscopy*

- 18% BW, 2x65° FOV, $\sim 3-9 \lambda_0/D$
- $\sim 3.9\%$ core throughput



3. **Shaped Pupil Coronagraph (SPC):** *outer disk imaging*

- 10% BW, 360° FOV, $\sim 6.5-20 \lambda_0/D$
- 6.0% core throughput

• Riggs SPIE 2014
 • Zimmerman, Riggs, et al. JATIS 2016

1. Introduction

2. CGI Spectroscopy Mode Improvements (SPLC)

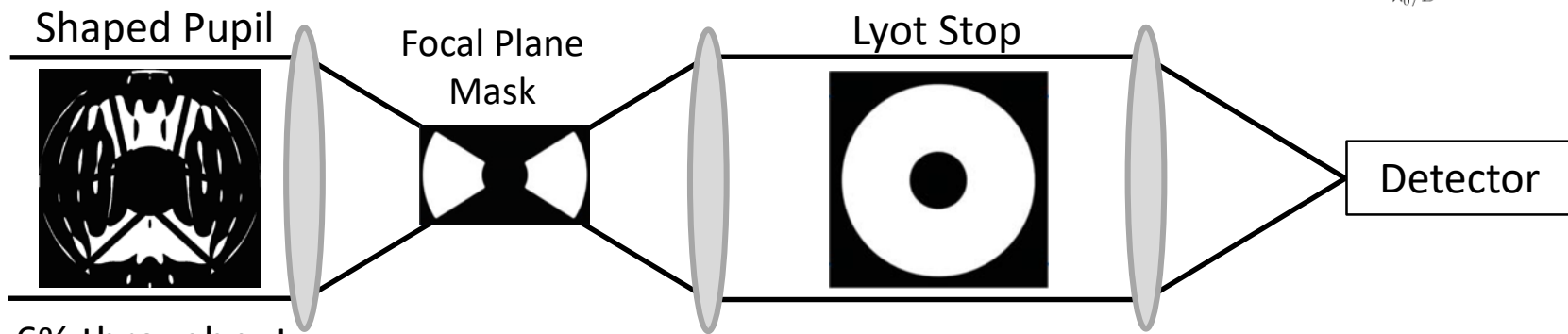
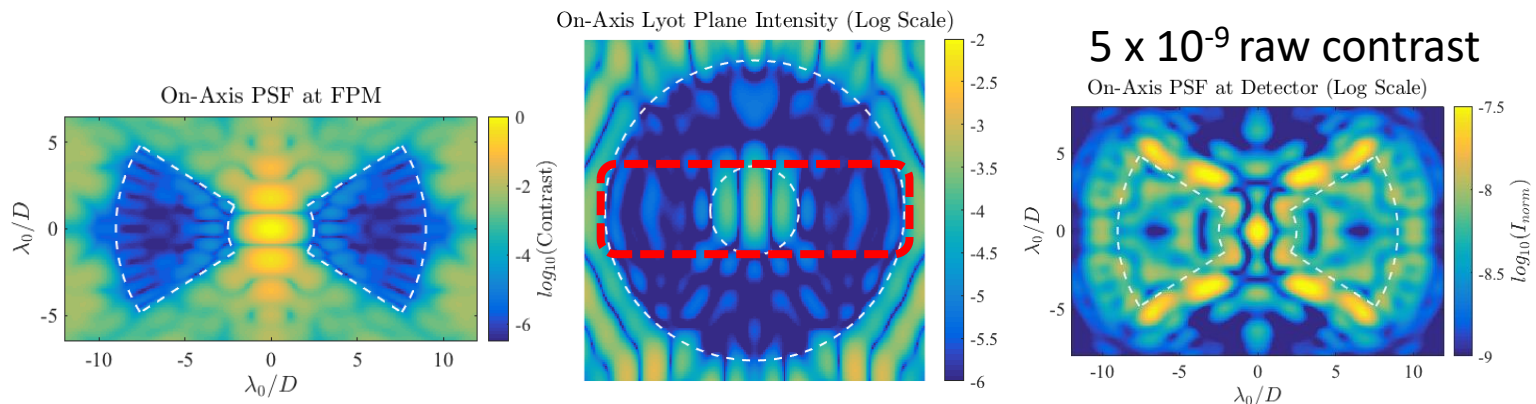
- a) New Lyot stop shape
- b) Better low-order aberration sensitivities
- c) Integrated design pipeline

3. CGI Disk Imaging Mode Improvements (SPLC)

4. APLC Investigations

SPC-IFS Design (2015-2016)

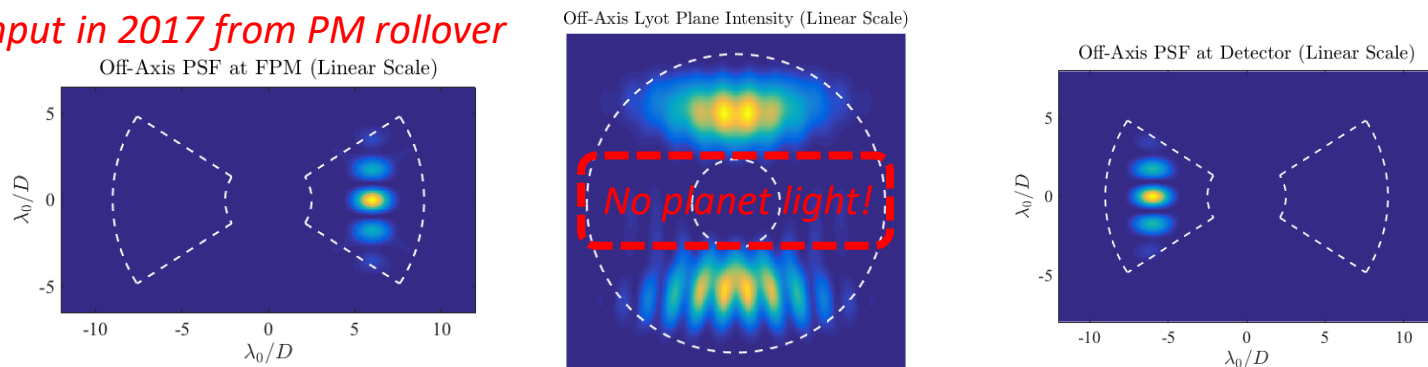
On-Axis Starlight



3.6% throughput

→ 3.0% throughput in 2017 from PM rollover

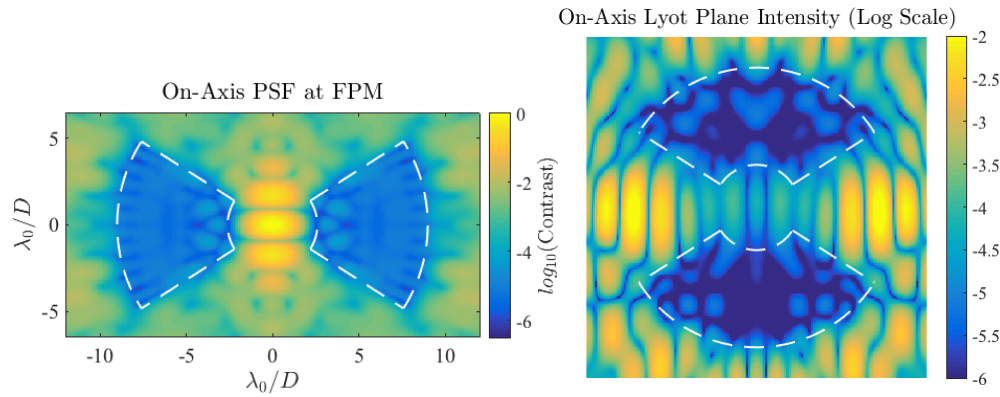
Off-Axis Planet Light



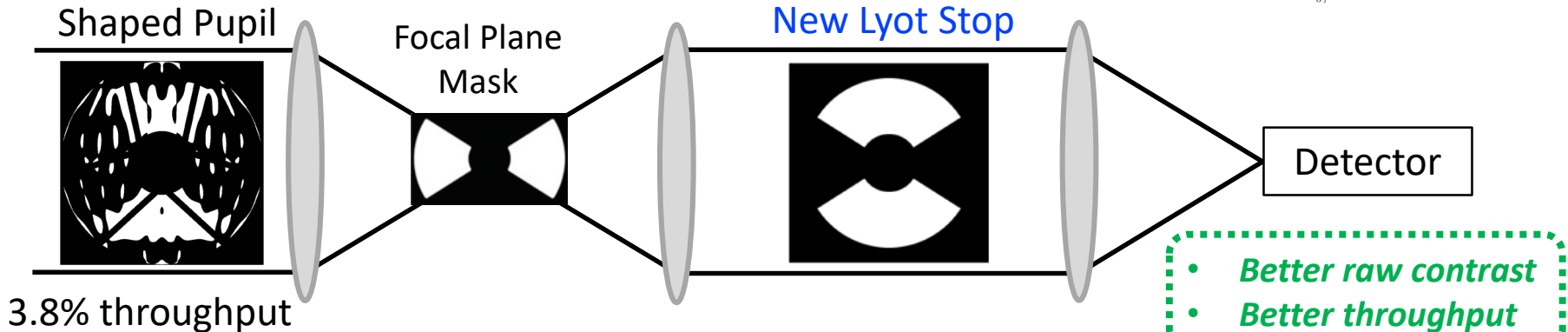
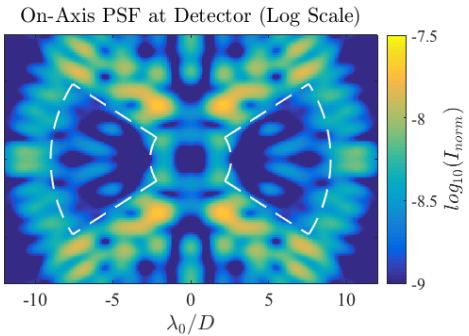


SPC-IFS Design (July 2017)

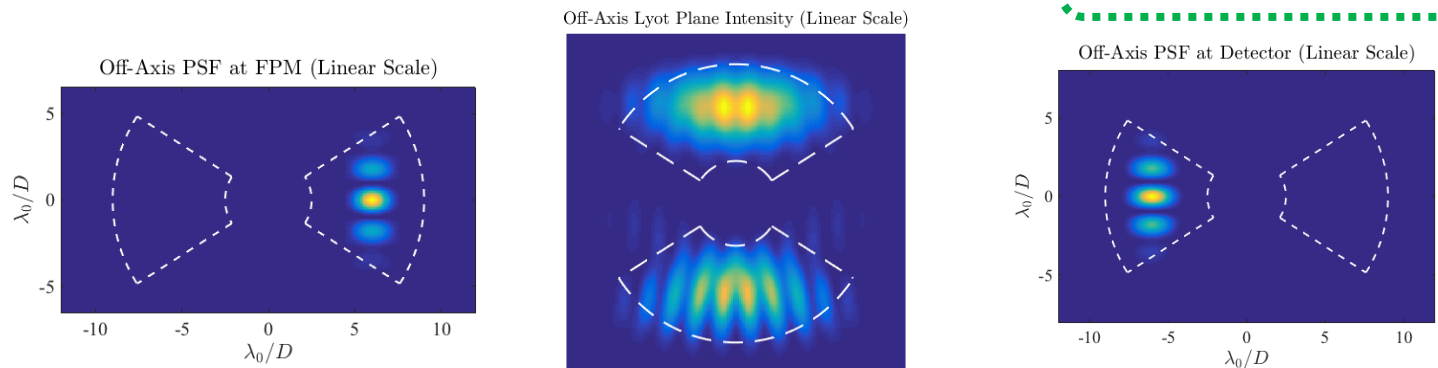
On-Axis
Starlight



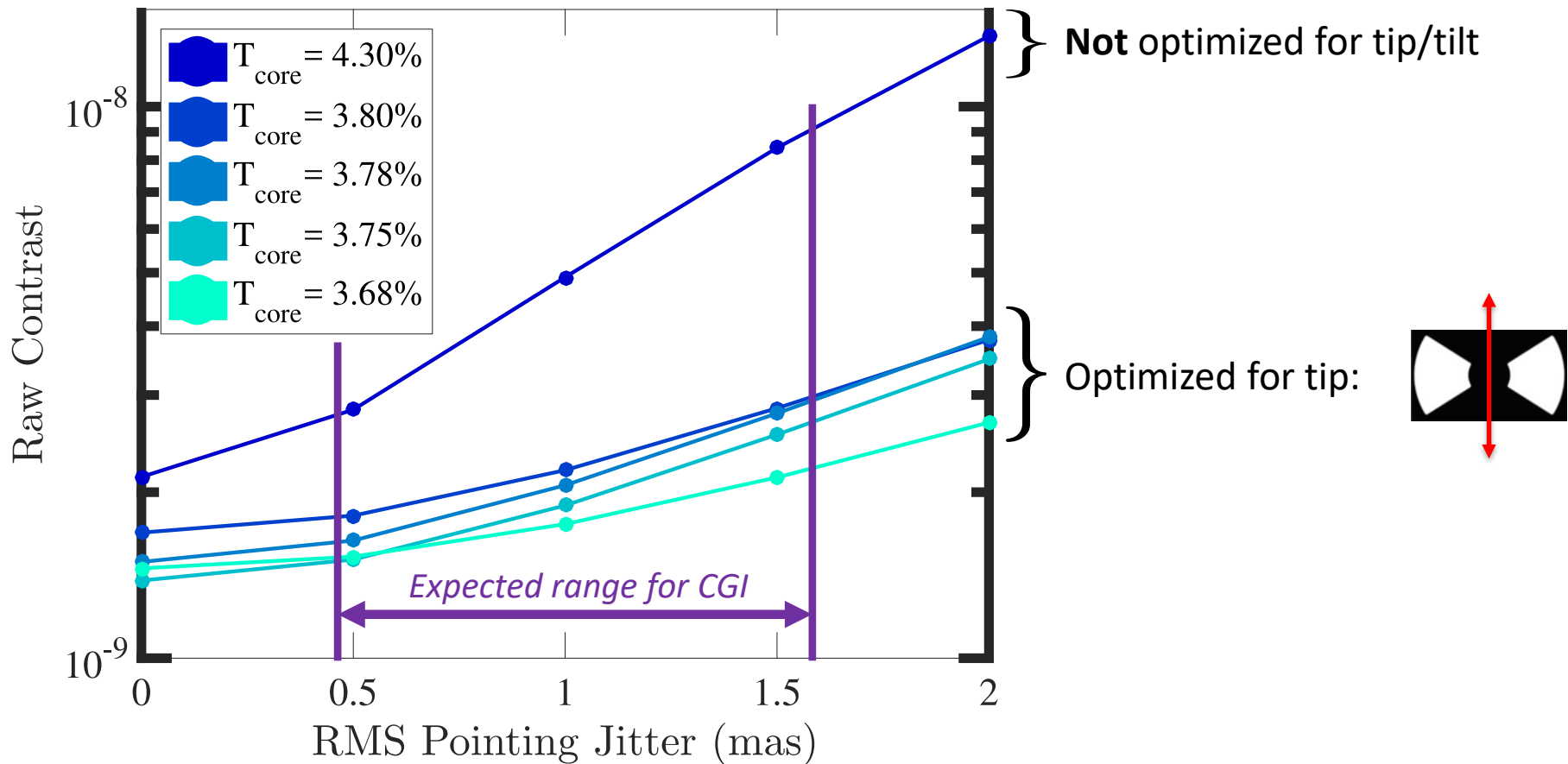
2×10^{-9} raw contrast



Off-Axis
Planet Light



Tip/Tilt Jitter Robustness



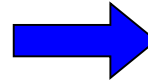
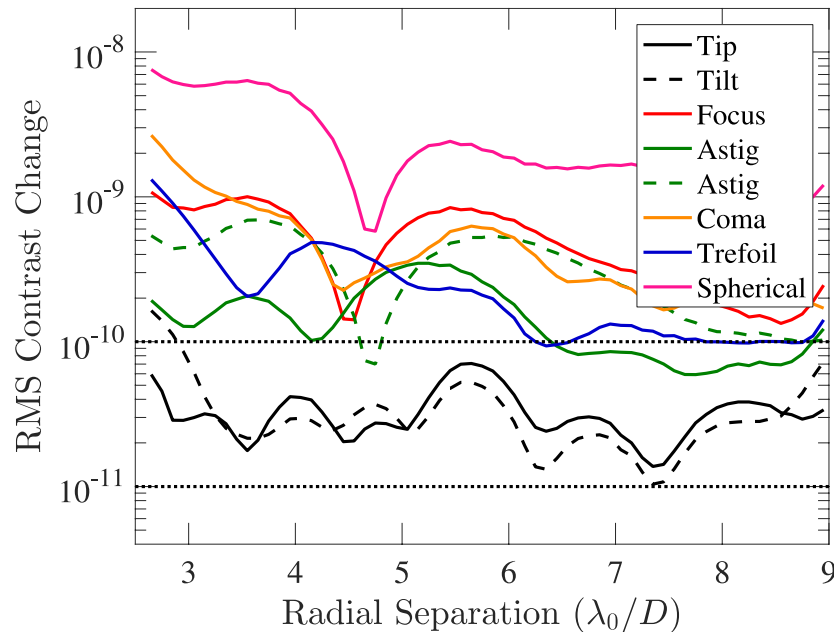
- **Must optimize for tip/tilt insensitivity**, or else contrast degrades too much

➤ **Tradeoff: T/T insensitivity vs throughput**

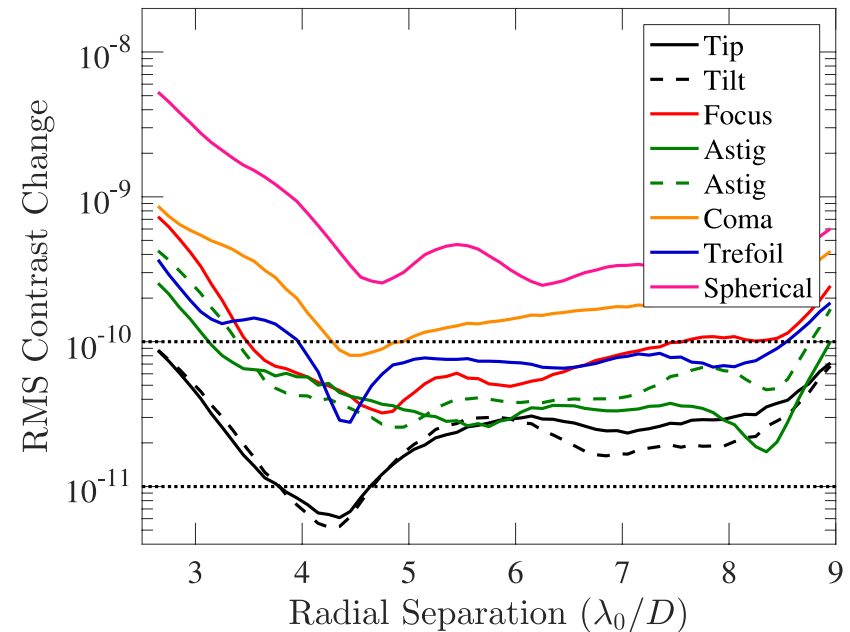
Wavefront Jitter Robustness

Contrast Degradation from 100 picometers RMS Zernike Aberrations

2016 Design (*Annular LS*)



July 2017 Design (*Bowtie LS+T/T Opt.*)



- **New design is several times less sensitive to most low-order aberrations**
 - More robust to polarization aberrations
 - More robust to wavefront jitter

SPC-IFS Design Pipeline

1) SPLC-IFS Optimization Code

Grid search over
design parameters.

Masks

2) Rapid Optical Simulator (MATLAB)

Simulate effects of:

- 1) **Tip/tilt:** jitter and stellar diameter
- 2) **Polarization** aberrations
- 3) [Soon] **Monte Carlo** aberrations & misalignments

Performance Data:

- raw contrast
- throughput
- core area

Optimization code modifications

4) Human Review

- Look for **statistically** highest yield designs.
- Adjust strategy to get more spectra.

Exposure times &
of spectra

3) RV Planet Exposure Time Calculator (MATLAB)

[Soon] Vary assumptions on planet
albedo & detector properties.



Assumptions: $\sigma_{T/T \text{ RMS}} = 1.5$ mas, $D_{\text{star}} = 1.0$ mas,

both polarizations, ≤ 240 hours/spectrum/bandpass

$f_{\text{pp}} = 0.2$

(Pessimistic Case)

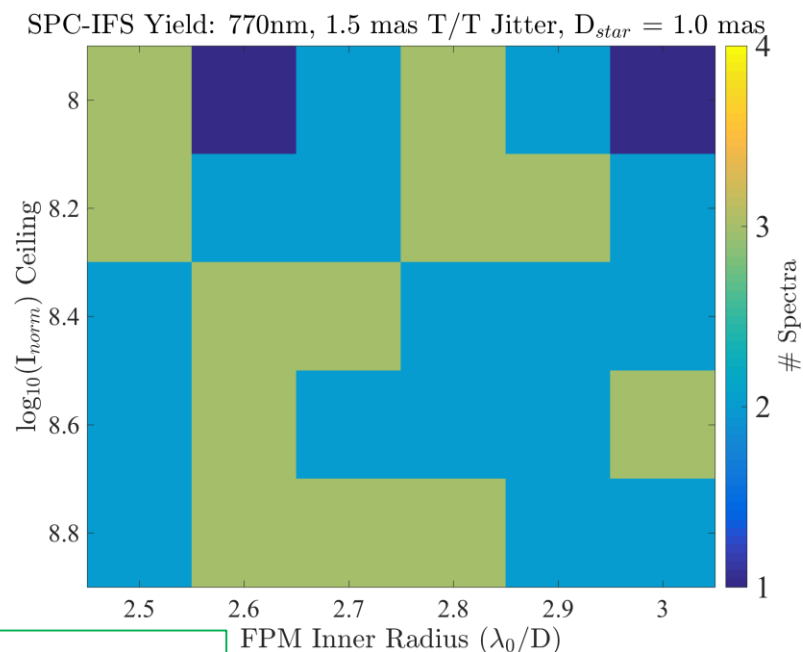
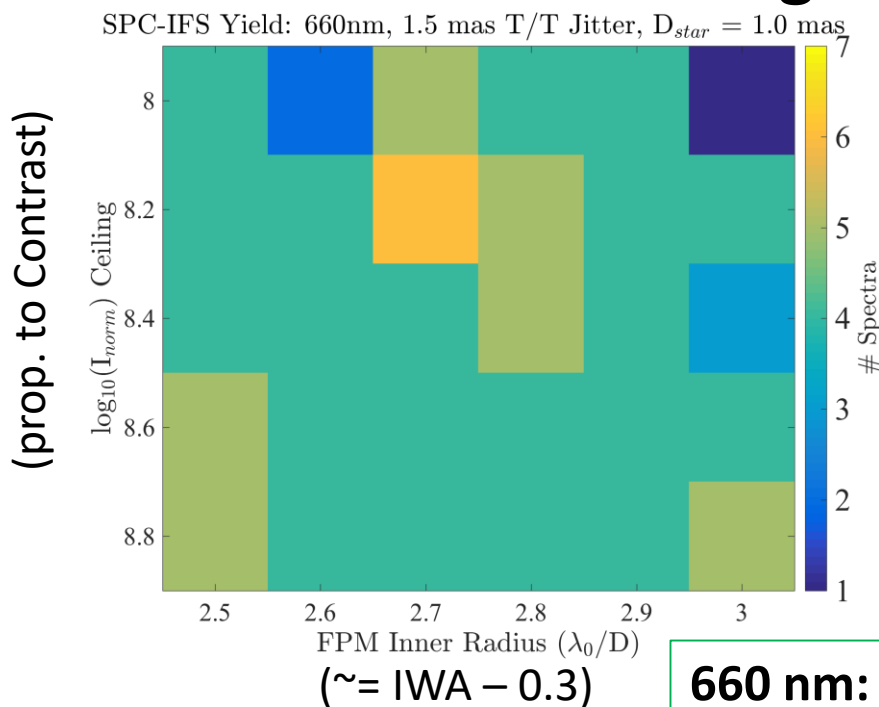
2016 Design (Annular Lyot Stop):

(Telescope OD not reduced)

660 nm: <3 spectra

770 nm: <1 spectra

June 2017 Design Survey (Bowtie Lyot Stop):



660 nm: ≤ 6 spectra

770 nm: ≤ 3 spectra

1. Introduction

2. CGI Spectroscopy Mode Improvements (SPLC)

- a) New Lyot stop shape
- b) Better low-order aberration sensitivities
- c) Integrated design pipeline

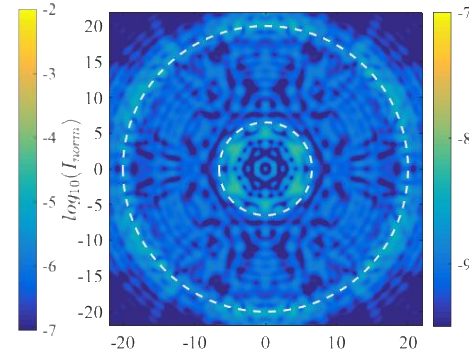
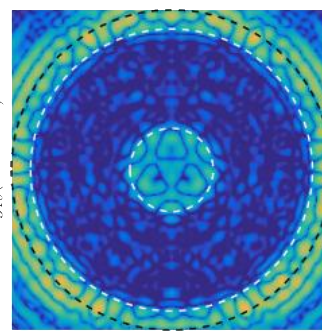
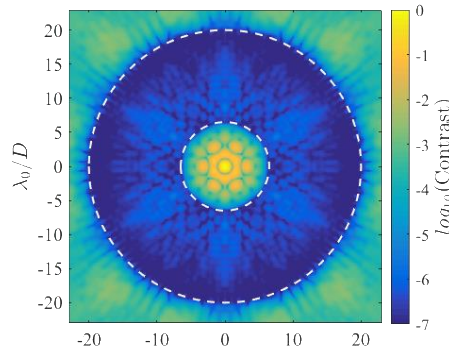
3. CGI Disk Imaging Mode Improvements (SPLC)

4. APLC Investigations



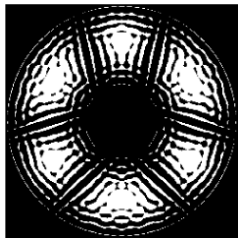
SPC-Disk Design (2015-2016)

On-Axis
Starlight
(Log Scale)

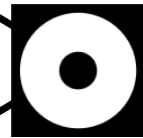


8e-10
Raw
Contrast

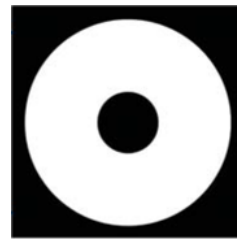
Shaped Pupil



Focal Plane
Mask



Lyot Stop

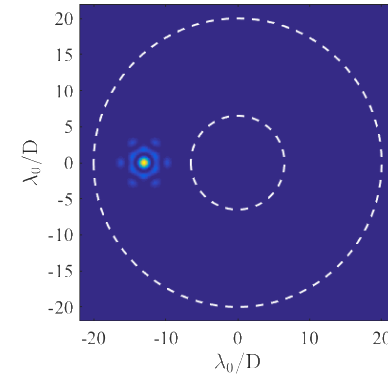
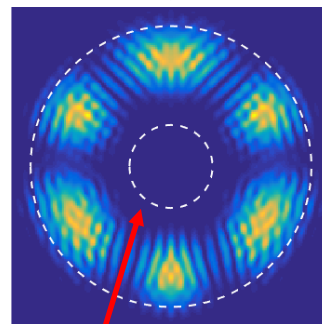
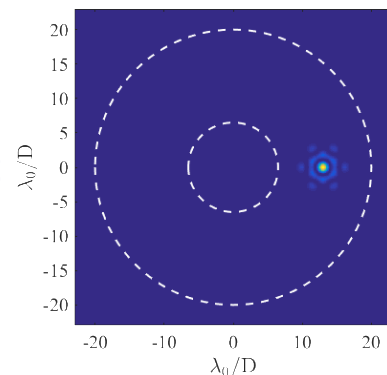


Detector

5.5% throughput

→ 5.2% throughput in
2017 from PM rollover

Off-Axis
Planet Light
(Linear Scale)

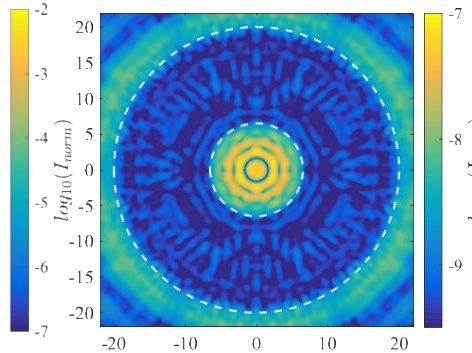
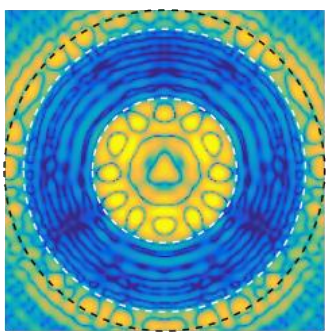
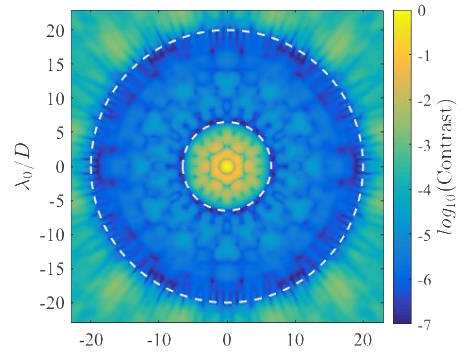


Lyot stop inner diameter is unnecessarily small → worse performance



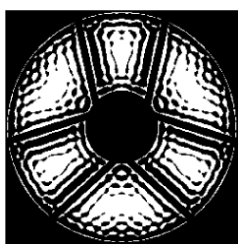
SPC-Disk Design (July 2017)

On-Axis
Starlight
(Log Scale)

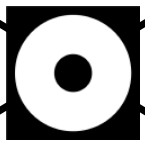


5e-10
Raw
Contrast

Shaped Pupil



Focal Plane
Mask



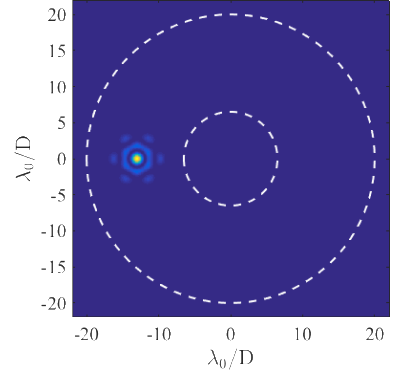
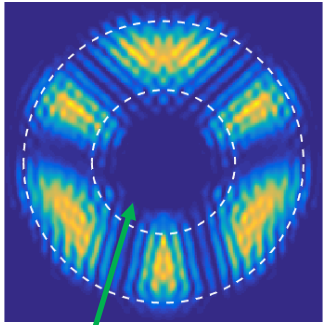
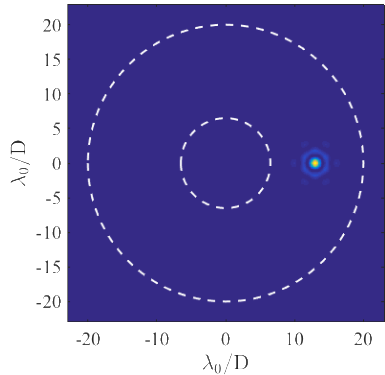
Lyot Stop



Detector

6.0% throughput

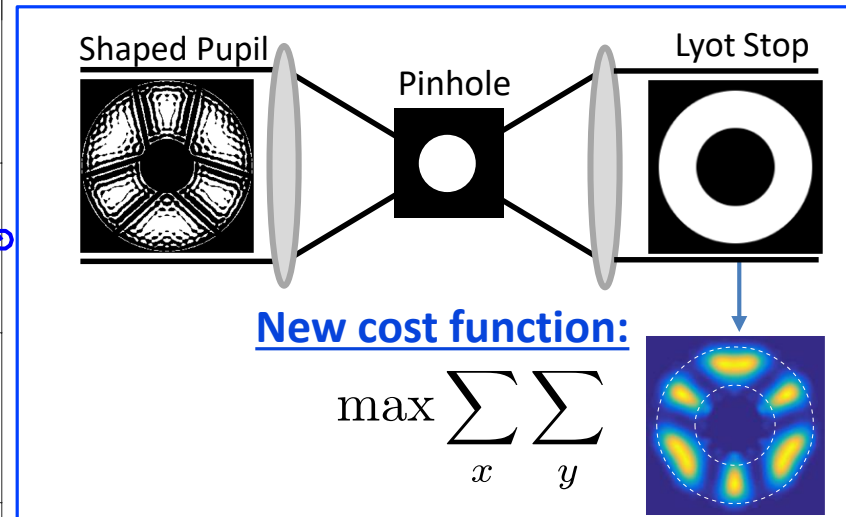
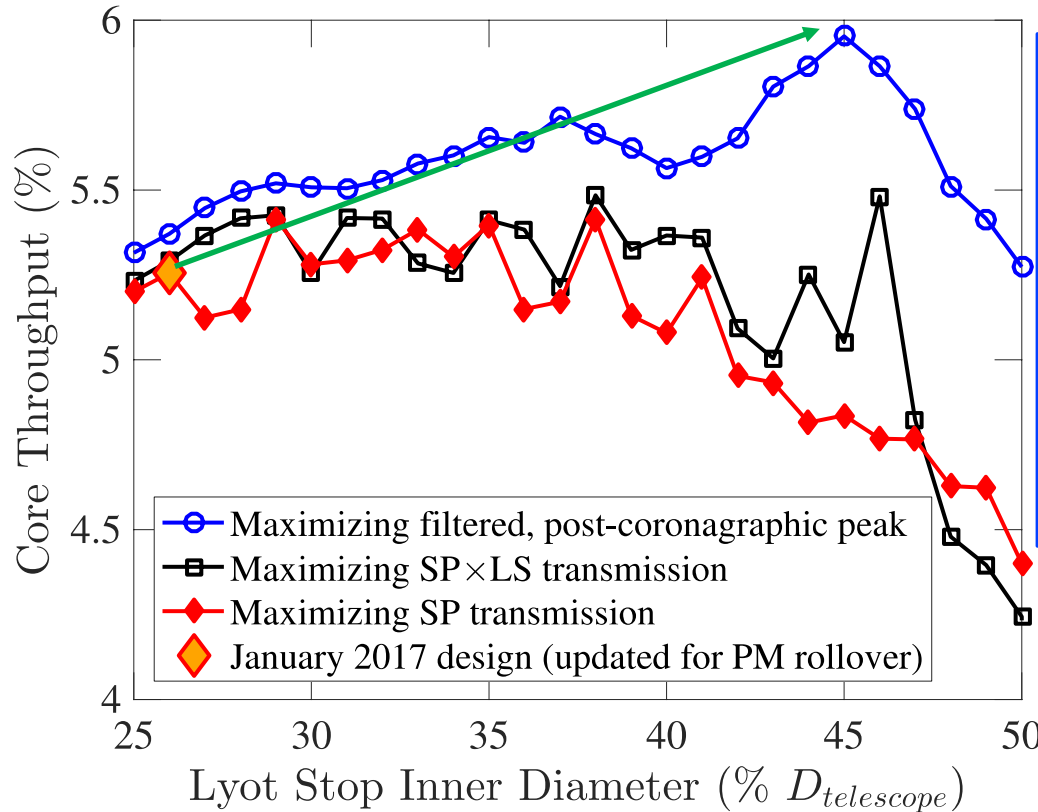
Off-Axis
Planet Light
(Linear Scale)



Lyot stop is better matched to shape of off-axis light

New Cost Function

- New Lyot stop was **insufficient** on its own
- Also needed **new cost function** in optimization



Old cost function:

$$\max \sum_x \sum_y$$

➤ New cost function now maximizes the **off-axis transmission** through the **whole coronagraph**

1. Introduction




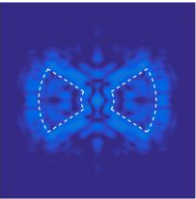
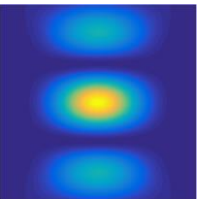



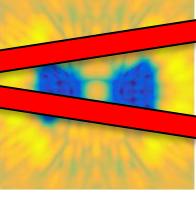
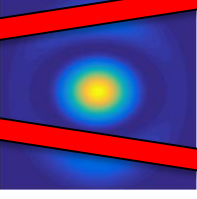



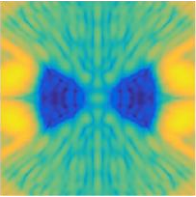
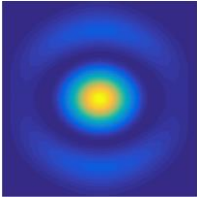
2. CGI Spectroscopy Mode Improvements (SPLC)

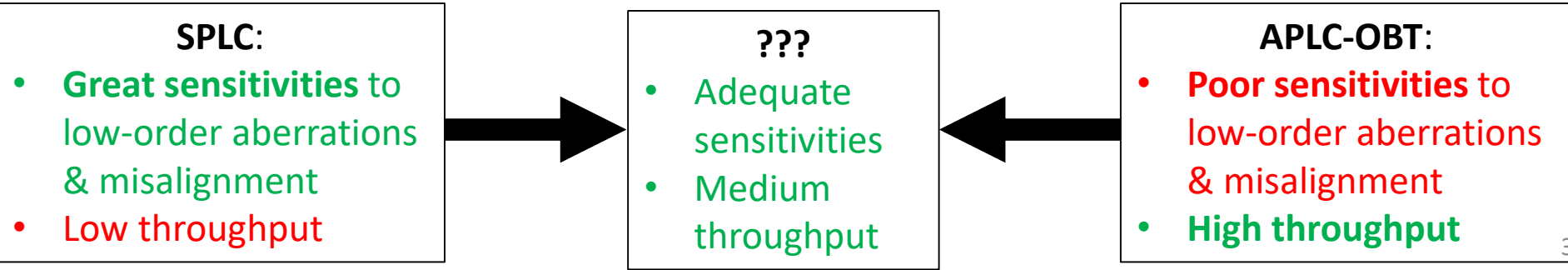
- a) New Lyot stop shape
- b) Better low-order aberration sensitivities
- c) Integrated design pipeline

3. CGI Disk Imaging Mode Improvements (SPLC)

4. APLC Investigations

SPLC & APLC Varieties

Type	Apodizer	FPM	LS	PSF _{star}	PSF _{planet}	Core (FWHM) Throughput	Notes
SPLC		 Bowtie				3.8%	<ul style="list-style-type: none"> 2e-9 raw contrast
APLC		 Occulting Spot				7.2%	<ul style="list-style-type: none"> 6e-9 raw contrast Poor astigmatism sensitivity at IWA
APLC-OBT		 Occulting Bowtie				10.0%	<ul style="list-style-type: none"> 4e-9 raw contrast Poor tip/tilt sensitivity
Notes:		Not to scale		$(15 \lambda_0/D)^2$, 10^{-9} to 10^{-2} Log scale	$(2.5 \lambda_0/D)^2$, Linear scale	No reflectivity losses	



1. CGI Spectroscopy Mode Improvements (SPLC)

- a) New Lyot stop shape
→ *Higher throughput & higher contrast*
- b) Better low-order aberration sensitivities
→ *Higher contrast*
- c) Integrated design pipeline
→ *Higher science yield*

2. CGI Disk Imaging Mode Improvements (SPLC)

- New cost function + New Lyot stop
→ *Higher throughput*

3. APLC vs SPLC

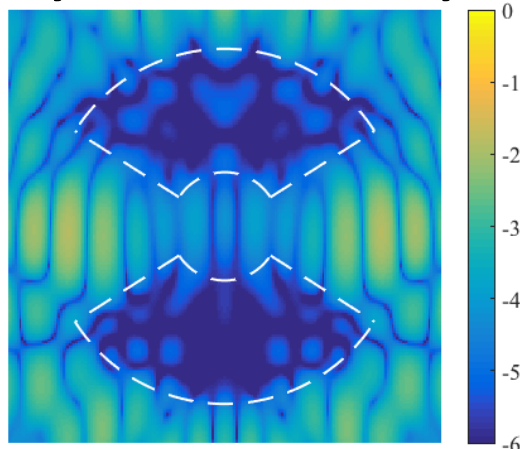
- Investigating **tradeoff**:
throughput vs aberration insensitivities

Backup Slides

APLC vs SPLC

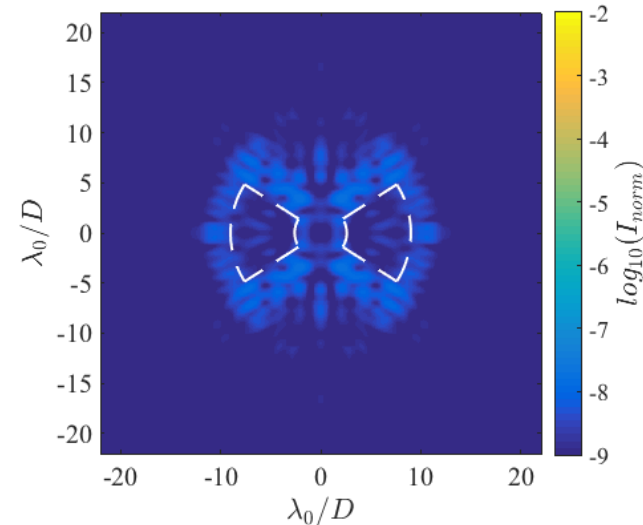
SPLC:

Lyot Plane Intensity

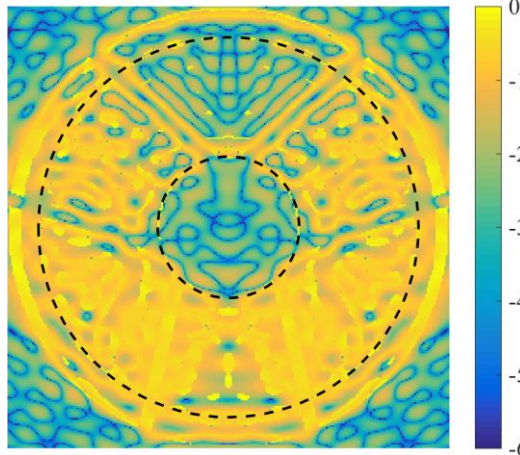


$2.5 \times 10^{-5} \%$ starlight transmitted

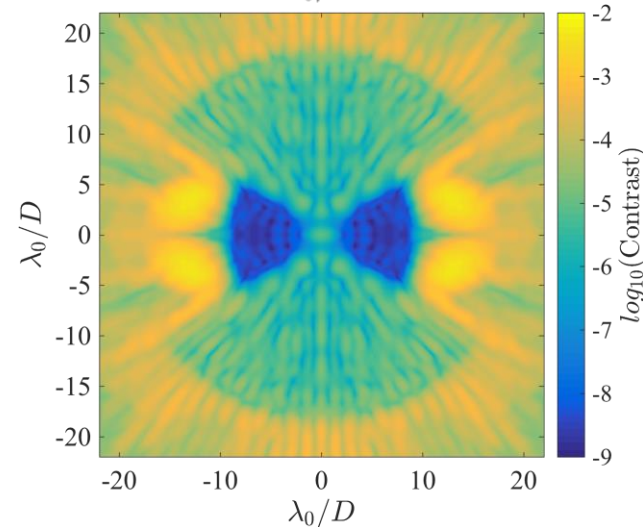
Stellar PSF



APLC-OBT:



16% starlight transmitted



- APLCs let **~1 million times** more light past Lyot stop
 - **Higher sensitivities** to low-order aberrations and Lyot stop misalignments



CGI Coronagraph Design

- Goals:**
- Maximize science yield.
 - Minimize risk.

Design Parameters

Sensitivities to:

- Pointing jitter
- Wavefront jitter (coma, astig, focus)
- Primary mirror **polarization** aberrations
- Mask **misalignment**

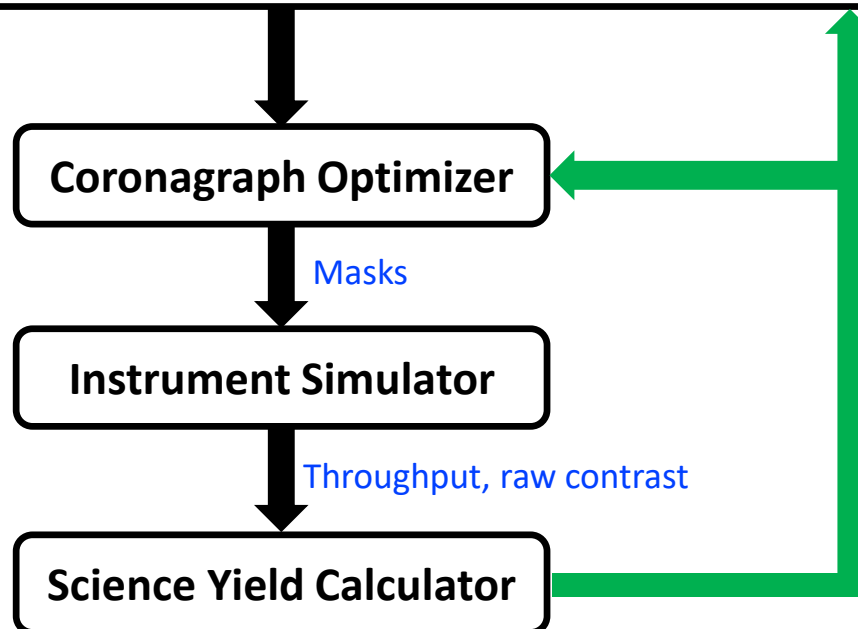
Performance Metrics

- Contrast
- Throughput
- Spectral **Bandwidth**
- **Field of View** (IWA, OWA, angle)

Mask Properties

- Mask **shapes**
- Mask **materials**

Most of the design work in past 1-2 years has been to address sensitivities to aberrations & misalignments.





The WFIRST Coronagraphs

Shaped Pupil Lyot Coronagraph (SPC):

Zimmerman et al. 2016

Shaped Pupil



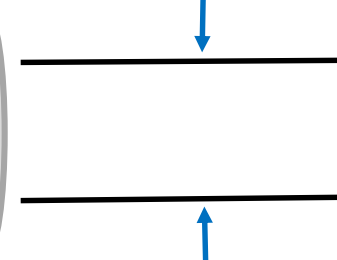
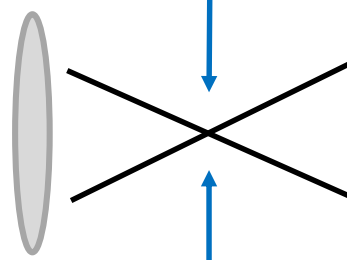
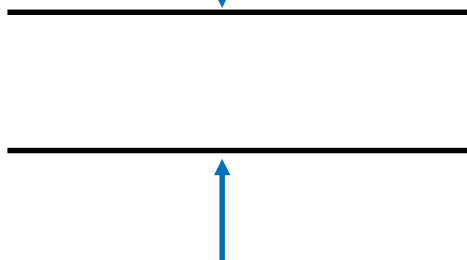
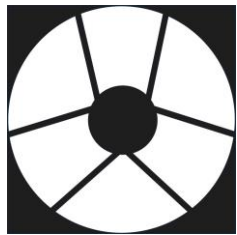
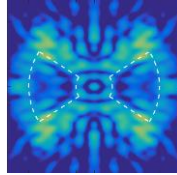
Hard-Edge FPM



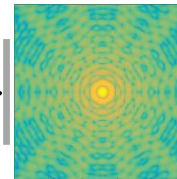
Lyot Stop



Stellar PSF



WFIRST PSF



Hybrid Lyot Coronagraph (HLC):

Trauger et al. 2016

DM1



DM2



Complex FPM



Phase

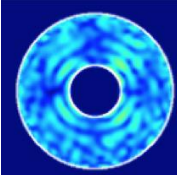


Amplitude

Lyot Stop



Stellar PSF



Large DM stroke as part of nominal design.

Benefits of Each Coronagraph:

- **HLC**: Full FOV, fewer masks, easier alignment
- **SPC**: Broader bandwidth, lower ab. sensitivities (esp. PM pol.), lower risk with DMs

SPC-IFS Design Pipeline

1) SPLC-IFS Optimization Code

Grid search over
design parameters.

Python wrapper

AMPL base code

Masks
from each
design

2) Rapid Optical Simulator (MATLAB)

Simulate effects of:

- 1) **Tip/tilt:** jitter and stellar diameter
- 2) **Polarization** aberrations (Phase A model).
- 3) **[Soon] Monte Carlo the Fresnel model:**
 - 1) Mask **misalignments**
 - 2) **PSD aberration maps** for each optic

Tables: Raw contrast,
throughput, core area

Optimization code modifications

4) Human Review

- Look for **statistically** highest yield designs.
- Adjust strategy to get more spectra.

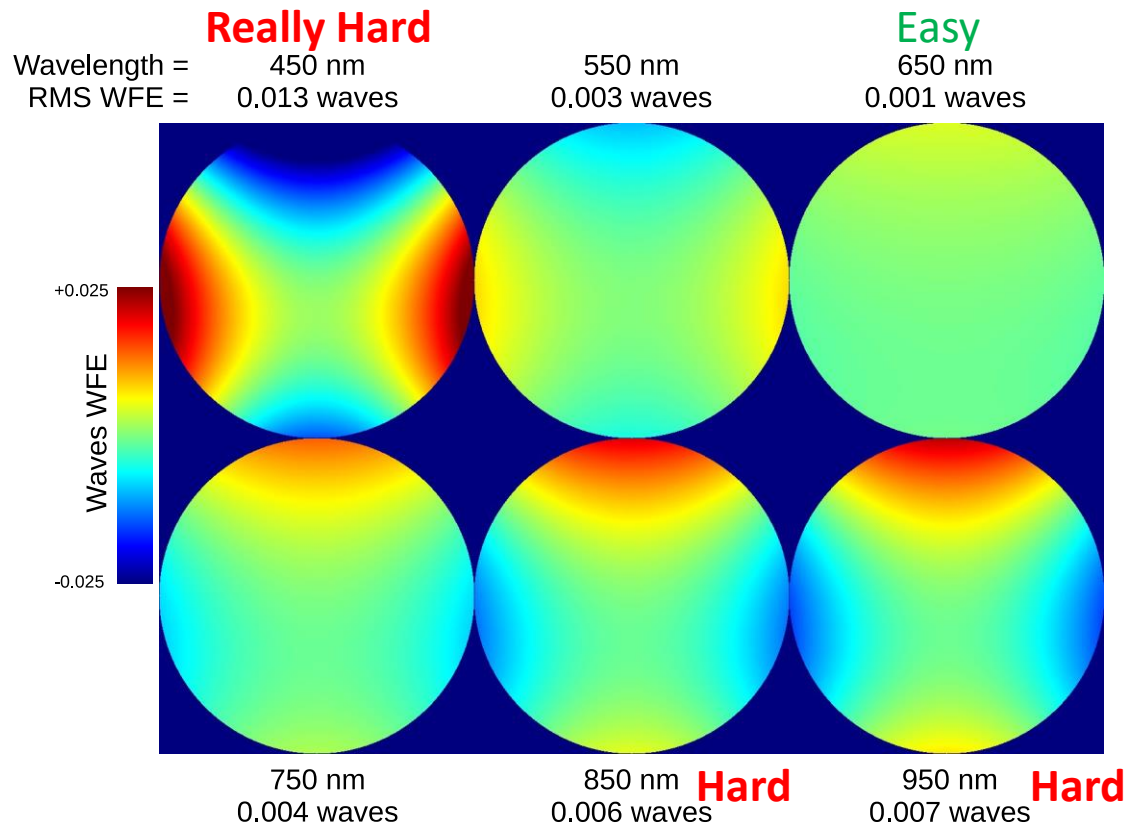
3) Nemati's RV Planet Exposure Time Calculator (MATLAB)

Vary assumptions on planet albedo
& detector properties.

Exposure times &
of spectra

➤ The polarization from the primary mirror is a **MAJOR** design constraint.

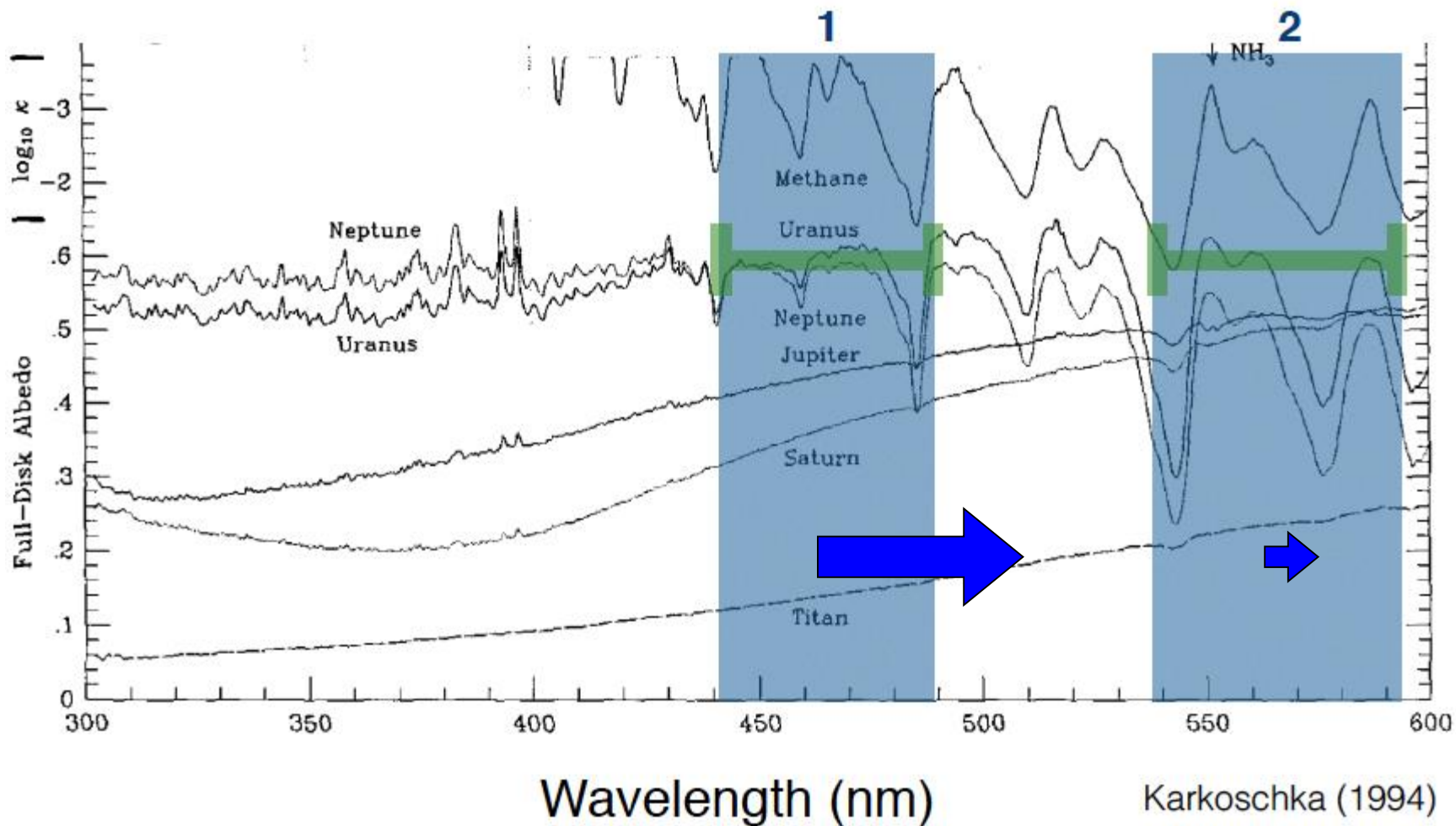
Cycle 6 Polarization: $WFE_Y - WFE_X$



This figure was already cleared in John Krist's presentation "Digging A Dark Hole: Models" in April 2016.

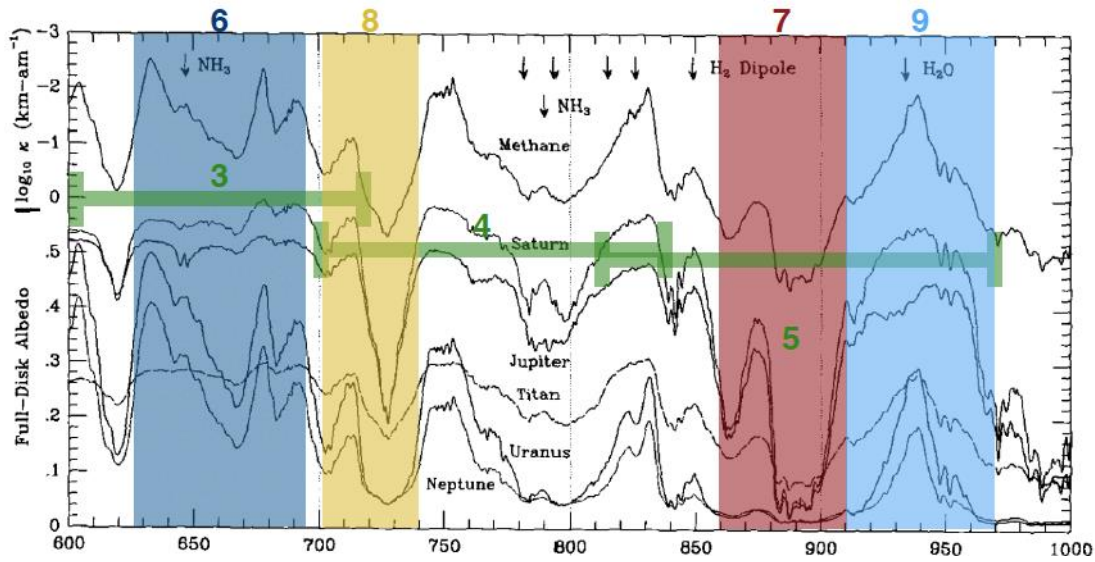
- Differential polarization is mostly astigmatism
 - Negligible near 600nm → **HLC**
 - Huge WFE far from 600nm → **SPC, or HLC+polarizer**
- Huge influence on our operational modes

CGI Science Bands 1 and 2



- Bands 1 & 2 shifted to longer wavelength because polarization WFE is too strong at B-band.

CGI Science Bands



NOTE: No polarizers or field stops in IFS channel.

CGI Bands	λ_{center} (nm)	BW	Science Purpose	Imager or IFS	Coronagraph Type	Can Use Polarizer (for Science)	Must Use Polarizer (for Aberrations)
1	508	10%	continuum, Rayleigh	Imager	HLC	X	X (HLC)
2	575	10%	continuum, Rayleigh	Imager	HLC	X	
3	660	18%	CH ₄ spectrum	IFS	SPC		
4	770	18%	CH ₄ spectrum	IFS	SPC		
5	890	18%	CH ₄ spectrum	IFS	SPC		
6	661	10%	CH ₄ , continuum	Imager	SPC	X	X (HLC)
7	883	5%	CH ₄ , absorption	Imager	SPC	X	
8	721	5%	CH ₄ quantification	Imager	SPC (& HLC?)	X	
9	950	6%	water detection	Imager	SPC	X	